UNITED STATES

PATENT APPLICATION

HILL & SCHUMACHER

TITLE: SLIDING CONCAVE FOUNDATION SYSTEM

INVENTORS: Mehrdad HAMIDI

M.Hashem EL NAGGAR

Abolhassan VAFAI

Goodarz AHMADI

SLIDING CONCAVE FOUNDATION SYSTEM

CROSS REFERENCE TO RELATED PATENT APPLICATION

This patent application relates to United States Provisional Patent Application Serial No. 60/409,569 filed on September 11, 2002 entitled SLIDING CONCAVE FOUNDATION SYSTEM which is incorporated herein by reference.

FIELD OF THE INVENTION

The present invention relates to foundation systems and in particular foundation systems adapted to withstand earthquakes.

BACKGROUND OF THE INVENTION

The occurrence of earthquake is a worldwide disaster often causing the loss of many lives and financial ruins. Studies have shown that an earthquake with a magnitude of six to seven at a distance of 8km from the causative fault can produce forces that are about 10 to 20 times the minimum forces given in existing seismic design codes. The elastic design of the structures for these forces, results in irrational costly construction. The inelastic design concept and ductility provision for structures can prevent the collapse of the buildings and reduce the cost of construction. However, the building and its contents could still be severely damaged. Therefore, the seismic isolation concept is considered a suitable solution in designing structures that can protect the buildings and its contents from serious damage.

S ismic isolation is the separation of the building (or any other typ of structure)

from th harmful motions of the ground by providing flexibility and nergy dissipation capability through the insertion of the so-called isolators between the foundation and the superstructure.

The first application of the isolators was relatively recent. The first base isolated building in United States of America was built in 1985. In terms of behavior, isolators are classified in two major groups: elastomeric and frictional isolators. Kelly, Su et. al. and Skinner provided comprehensive reviews on isolation devices and techniques.

The use of base isolation systems has two major advantages. First, the vertical and horizontal loads are resisted in different ways. This results in more stable structural system and eliminates the need for a mechanism to dissipate energy while preventing structural collapse. Second, in the presence of a small restoring force, the sliding systems are (practically) insensitive to frequency content of the base excitation and always limit the transmitted shear force to the building. This feature (insensitivity to frequency content of the base excitation) is the most important benefit of a sliding system.

A large number of theoretical and experimental studies have shown that these systems could decrease the damaging effects of the earthquakes. The oldest base isolation technique that had previously been successfully implemented in the building construction was the sliding support system that is also referred to as the Pure Friction (P-F) system. Numerous studies have been carried out concerning the response analyses of the structures on sliding support. Westermo and Udwadia and Mostaghel et. al. studied the responses of the sliding structures under harmonic base excitations. Mostaghel and Tanbakuchi investigated the ability of the sliding supports to isolate the

superstructure from the vibrations of the base during strong earthquakes excitation. In most of these studies, a 2-degree of freedom (DOF) model was employed, one for the single degree of freedom (SDOF) structure and one for the sliding raft. Yang et al, Fan et al and Vafai et al studied the effects of sliding supports on the responses of the multistory structures subjected to different base excitations. In these studies, it was assumed that the friction was of the Coulomb type and it was independent of the contact pressure and the relative velocity of the sliding surface and also the dynamic and static coefficients of friction were considered equal.

Zayas in 1986 introduced one of the most effective isolation systems, namely the Friction Pendulum System (FPS), which utilizes friction to dissipate the transmitted energy to the structure. Thereafter, numerous theoretical and experimental studies were conducted to investigate the FPS characteristics and its application in bridges and buildings. Principally, a building supported on FPS isolators behaves as a simple pendulum. The basic concept of the FPS system is shown in Figure 1. It is shown that the fundamental period of the FPS is determined by Equation (1):

$$T = 2\pi\sqrt{\frac{R}{g}} \tag{1}$$

Where, R is the curvature of the sliding surface and g is the gravity. Equation (1) gives the fundamental period of a rigid body supported on a FPS isolator. However, if the structure on the FPS is relatively short and rigid, Equation (1) can be used as the period of the combined system of the FPS and superstructure.

Accordingly it would be advantageous to provide a foundation system that reduces the lateral seismic forces transmitted to the structure.

SUMMARY OF THE INVENTION

The present invention, a new base isolation system, namely the Sliding Concave Foundation (SCF) is introduced. The new system utilizes friction to dissipate the earthquake energy. However, it has other features that make it an attractive base isolation system.

A foundation system for a building or other load includes a lower part and an upper sliding raft. The lower part has a generally concave surface at the top thereof. The upper sliding raft has a convex surface at the bottom thereof adapted to rest on the concave surface of the lower part and allow for sliding rotational movement therebetween. The building or other load is attached to the upper sliding raft.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will now be described by way of example only, with reference to the accompanying drawings, in which:

Fig.1 is a schematic showing the basic principles of prior art friction pendulum system;

Fig. 2 is a side view of the sliding concave foundation system of the present invention;

Fig. 3 is a schematic showing the basic principles of the sliding concave foundation system of the present invention;

Fig. 4 is a model of a single degree of freedom structure on the sliding concave foundation syst m of the present invention and showing the operating forces at the

contact points thereof;

Fig. 5 is a model of a single degree of freedom structure on the sliding concave foundation system of the present invention for the determination of the fundamental period of the superstructure;

Fig. 6 is graphs of the fundamental period for the superstructure and the foundation;

Fig. 7 is comparative models comparing a fixed base, a sliding support , a sliding concave foundation and a friction pendulum system;

Figs. 8 and 9 are comparative structural responses using different isolation systems and without them subjected to Tabas earthquake;

Figs. 10 and 11 are comparative structural responses using different isolation systems and without them subjected to long period harmonic excitation;

Fig. 12 is a graph showing a comparison of the structural damage to a structure on a fixed base versus the sliding concave foundation of the present invention;

Fig. 13 is a schematic showing the test model used in regard to the present invention; and

Fig. 14 is a graph showing a comparison of results of a sliding concave foundation experiment versus a theoretical sliding concave foundation and a theoretical fixed base foundation.

DETAILED DESCRIPTION OF THE INVENTION

The main components of the new system (SCF) are shown in Figure 2 at 20. The building foundation 22 in this system consists of two parts. The lower part 24 has

a cylindrical concave surface at the top and hereafter is referred to as the fixed foundation or, briefly, the foundation. This part moves with the ground and has no sliding displacement relative to the ground. The top part 26 has a cylindrical convexity and is called the sliding raft. The sliding raft 26 is attached to the building and can be considered as its floor so that the columns are connected rigidly to this raft. In practice, the sliding raft 26 can be constructed in different ways. One way involves a concrete platform resting on a number of short and rigid stands that follow the curvature of the fixed base foundation 24 at their ends as shown in Figure 2. The sliding raft has a sliding-rotational movement on the sliding surface of the fixed foundation 24.

The interfaces of these two parts 24, 26 are made of very low friction materials such as Steel-Teflon or Teflon-Teflon interfaces. Sliding of the raft 26 provides excessive flexibility at the foundation level that causes the separation of the superstructure from the damaging vibration of the base 24. In addition, a great amount of the earthquake energy is dissipated due to friction at the sliding surface. Therefore, base shear drifts and consequently the total damage to the building significantly decreases.

Since the sliding raft 26 always moves with the building, hereafter the combination of the building and the sliding raft is called superstructure 28. It should be mentioned that Figure 2 is a two dimensional model. In practice, however, the problem is three-dimensional and there are two cylindrical sliding surfaces that are perpendicular to each other. Since the sliding on each surface is independent of the other surface, the characteristics of the SCF can be investigated using a two dimensional mod l.

The basic conc pt of SCF is shown in Figure 3. The motion of the building on this isolation system is similar to a compound pendulum shown at 30 and 32. Therefore, both the linear inertia (mass) and the rotational inertia of the superstructure 28 contribute to the dynamic natural period of the system. The contribution of the rotational inertia is unique to the SCF system and is not available in other existing isolation systems. An interesting feature of the SCF system, is that the center of gravity of the superstructure falls under the center of curvature of the foundation as can be noted at 34 and 36 in Figure 3. Therefore, for any rotation θ of the superstructure around the center of curvature, the weight of the superstructure produces a restoring force that always opposes the overturning moment. This means that the SCF system improves the stability of the structure.

EQUILIBRIUM EQUATIONS

A simplified model of a SDOF structure supported by a SCF, which is used to develop the governing equations of motion, is shown in Figure 4 generally at 38. The frictional forces at the contact points i (F_{f_i}), shown generally at 40 in Figure 4b, can be determined from the equations of equilibrium (Equations 2 to 4). These forces develop due to the very small rotation θ of the superstructure around the center of the foundation curvature. The equilibrium of the system is considered along the tangential direction of the sliding surface and along the radial direction, i.e.

Tangential equation of equilibrium:

$$F_i \cos(\alpha_i + \theta) - W_i \sin(\alpha_i + \theta) - F_{f_i} = 0 \qquad (2)$$

$$F_i = \frac{F_{f_i}}{\cos(\alpha_i + \theta)} + W_i \tan(\alpha_i + \theta) \quad (3)$$

Radial equation of equilibrium:

$$N_i = F_i \sin(\alpha_i + \theta) - W_i \cos(\alpha_i + \theta) \quad (4)$$

where W_i, F_{f_i} and N_i are the weight, friction and the normal forces at the contact point i, respectively, and angles α and θ are defined in Figure 4. In Equations 2 through 4, F_i is the inertial force that acts at the ith contact point on the sliding surface (i.e. the shear force that acts on the sliding part at the ith contact point) and can be obtained by solving the dynamic equations of motion of the system.

For Coulomb type friction $F_{f_i} = \mu N_i$, where μ is the coefficient of friction, and Equation (4) can be rewritten as:

$$F_{f_i} = -\mu[F_i \sin(\alpha_i + \theta) + W_i \cos(\alpha_i + \theta)]\,\mathrm{sgn}(\dot{\theta}) \quad (5)$$

The negative sign of $\mathrm{sgn}(\dot{\theta})$ implies that the friction force is always in the opposite direction of the velocity.

Another interesting feature of the new system is that the value of lateral (inertial) force at the ith contact point (F_i) is proportional to the part of the weight that is supported at the same point (W_i), as suggested by Equations (3 to 5). This means that the center of lateral stiffness always coincides with the center of gravity of the system. This feature of the SCF system, which is similar to FPS, principally eliminates the undesired torsional vibrations and the consequent damage to the unsymmetrical buildings during an arthquake.

When the structure goes through a small rotation θ from its initial position, a restoring force develops in the center of gravity of the superstructure due to the weight of the superstructure. This restoring force and the frictional forces at the sliding surface would produce a restoring moment around the center of curvature of the foundation, which can be calculated from:

$$M = WR_{c.g}\theta - F_{f_i}R \qquad (6)$$

where R is the radius of the sliding surface of the foundation, $R_{c.g}$ is the distance between the center of gravity of the superstructure and the center of curvature of the foundation and W is the total weight of the superstructure. In Equation (6), the first term in the right hand side is the share of the gravity in the restoring moment ($M_{gravity}$) and the second term is the share of the frictional force, which is opposite to the first term.

The rotational stiffness of the system around the center of the foundation can be determined by dividing the restoring moment due to gravity ($M_{gravity}$) by the angle of rotation θ, i.e.

$$K_\theta = \frac{M_{gravity}}{\theta} = WR_{c.g} \qquad (7)$$

The rotational inertia around the center of curvature of the foundation is given as:

$$I_o = I_{c.g} + \left(\frac{W}{g}\right)R_{c.g}^2 \qquad (8)$$

Thus the oscillation period of the superstructure around the center of curvature of the foundation becomes:

$$T = 2\pi\sqrt{\left(\frac{I_o}{K_\theta}\right)} = 2\pi\sqrt{\left(\frac{I_{c.g}}{WR_{c.g}} + \frac{R_{c.g}}{g}\right)} \quad (9)$$

It can be noted from Equation (9) that the period of the system is the same as the period of a compound pendulum consisting of two parts. In comparison with the period of a FPS isolator (Equation 1), the presence of the first part (which is absent in the FPS case) results in a large increase in the period of the system. The form of the second part is the same as that of a FPS isolator, however, the value of $R_{c.g}$ for the SCF is much larger than that of the FPS and this increases the period furthermore. Equation (1) suggests that the period of the FPS isolator is independent of the mass of the superstructure. Similarly, the period of the SCF system is independent of the total mass but it depends on the distribution of the mass ($I_{c.g}/W$).

The fundamental period of a SDOF structure supported by SCF system is given in Equation (9)), which simply gives the fundamental period of a compound pendulum. In this equation, it is assumed that the period of the main structure is very small compared to the fundamental period of the total system, thus the period of the superstructure is not affected considerably by the stiffness of the main structure. To verify this assumption, the fundamental period of a SDOF structure supported by a SCF (shown in Figure 5) is determined through the solution of the governing equations of motion. This was achieved by computing the time required for the system to complete one cycle under free vibration conditions.

To investigate the effects of the SCF on the behavior of structures, a computer program was developed that is capable of analyzing the response of a SDOF structure supported by a SCF system (th program is also capable to analyze the responses of

the SDOF structure supported by FPS, sliding base and fixed base foundation).

The structure whose stiffness, damping, mass and geometrical properties are listed in Figure 5 was used as an example to verify the performance of Equation (9). Specifically the particulars are as follows: m_1 = 350.2 kg; I_1 = 4109 kg-m^2; m_b = 350.2 kg; I_b = 4109 kg-m^2; K=8.64 x 10^4 N/m; C = 550.1 N.sec/m; T=0.4 sec; R = 15.0 m; h_1 = 6.0 m; h_b = 1.0m; μ = 0.08; and ξ = 0.05. The fundamental period of the structure was calculated using Equation (9) and its value was 7.20 sec.

The system shown in Figure 5 was subjected to an harmonic base excitation for 5 sec., then the amplitude of the excitation was set to zero to allow the system to go through a free vibration with no external excitation. The response of the superstructure was calculated for a period of time long enough for the system to complete at least one full cycle of oscillation after the base excitation had stopped. To minimize the strong dissipative effects of the friction (so that the free vibration of the system could last long enough), the Coulomb coefficient of friction for this example was assigned a small value (μ=0.003). The results of the analysis are presented in Figure 6 in terms of the absolute acceleration time histories of the story at 44 and the sliding raft at 46. The fundamental period of the structure obtained from the absolute acceleration time histories of the story and the sliding raft is 7.21 and 7.23 sec., respectively, as shown in Figure 6. As can be noted, the fundamental period value calculated using Equation (9) agreed well with those obtained from the free vibration response analysis.

A computer program developed was used to calculate the response of a SDOF structure for different support conditions: fixed base 48, sliding support 50, SCF 52 and friction pendulum syst m (FPS) 54. The necessary information used in this xample is

given in Figure 7. Specifically for the fixed base has the following particulars: m_1 = 350.2 kg; K=8.64 x 10^4 N/m; C=550.1 N.sec/m; T = 0.4; and sec ξ = 0.05. The particulars for the sliding support are as follows: m_1 = 350.2 kg; m_b = 350.2 kg; K=8.64 x 10^4 N/m; C=550.1 N.sec/m; T = 0.4; μ = 0.08; and sec ξ = 0.05. The particulars for the SCF are as follows: m_1 = 350.2 kg; I_1 = 4109 kg-m^2; m_b = 350.2 kg; I_b = 4109 kg-m^2; K=8.64 x 10^4 N/m; C = 550.1 N.sec/m; T=0.4 sec; R = 15.0 m; h_1 = 6.0 m; h_b = 1.0m; μ = 0.08; and ξ = 0.05. The particulars for the FPS are as follows: m_1 = 350.2 kg; m_b = 350.2 kg; K=8.64 x 10^4 N/m; C = 550.1 N.sec/m; T=0.4 sec; R = 15.0 m; h_1 = 6.0 m; h_b = 1.0m; μ = 0.08; and ξ = 0.05. The friction is assumed to be of the Coulomb type and the radius of the curvature of the foundation for the SCF is 31m. The radius of the FPS used in the analysis is assumed to be 1.0m, a value that is larger than those normally used in practice.

The fundamental period of the structure supported by the SCF is 10.4 sec. (from Equation 9), which is much larger than that of the structure supported by the FPS (2.0 sec. from Equation 1). The fundamental period of the structure supported by the SCF is far from the predominant frequency associated with destructive earthquakes. Therefore, the SCF renders the structure insensitive to the frequency content of the base excitation.

The results of the analysis of the system response under the Tabas earthquake excitation are presented in Figures 8 and 9. Figure 8(a) 56 shows the displacement of the story relative to the base and Figure 8(b) 58 shows the absolute acceleration of the story, for diff rent support conditions. Figures 8 shows that the ability of the SCF to reduc the responses of th structure is comparabl to thos of the sliding support

system and FPS. The three systems significantly reduce the displacement and acceleration of the story compared to the case of the fixed base. Figure 9(a) 60 shows that the SCF system, similar to the FPS and sliding support system, is very efficient in reducing the base shear forces transmitted to the structure. Figure 9(b) 62 presents a comparison between the sliding displacements of the three base isolation systems (i.e. SCF, FPS and sliding support). Figure 9(b) 62 shows that the maximum sliding displacement of the structure supported by the SCF system is significantly reduced compared with that of the sliding support system, but is higher than that of the FPS. However, the SCF system may perform even better than the FPS as shown below.

The same structures shown in Figure 7 are subjected to a harmonic excitation (representative of earthquake excitations in soft soils) with an amplitude of 0.5g and a circular frequency of 4 rad/sec (period of 1.57 sec). The results are shown in Figures 10 and 11, for different support conditions. Figure 10 shows the relative displacement 64 and absolute acceleration 66 of the story and Figure 11 presents the base shear 68 of the SDOF structure and the sliding displacement 70 of the raft. It can be noted from Figure 10 that the SCF reduced the structural response compared to the other support conditions. Furthermore, Figure 11 shows that the base shear transmitted to the structure and the sliding displacement of the foundation are significantly reduced for the SCF system relative to the other systems, including the FPS. It should be noted from Figure 11(b) that the residual displacement for the SCF system is much less than that of the FPS.

Th results pres nted in Figures 8 through 11 show that the relative advantages of the SCF and FPS dep nd on th amplitude and frequency contents of the excitation.

Studies show that for strong r earthquakes the SCF is more efficient than FPS. A very important feature of SCF is that because of its long period, it never experiences resonance during an earthquake. On the contrary, most of the isolating systems that have been introduced so far can undergo resonance under especial conditions. As shown in Figure 10 and 11, both the sliding support system and FPS fall in resonance under a long-period harmonic excitation. Similar results were obtained through the study of numerous examples under different types of base excitement.

The inelastic energy absorption demand is a suitable criterion for predicting the level of damage to a structure. Figure 12 shows a comparison between the inelastic energy absorption demands of two similar structures; one supported by a SCF and the other with a fixed base. The structures were loaded according to the seismic code of Iran and designed according to AISC allowable stress method. The inelastic energy absorption demand of the structure was determined utilizing the method of Nurtug and Sucuoglu. The yielding energy (defined as the reserved energy in the structure at the commencement of the yielding) is used to normalize the absorbed energy. Figure 12 confirms the positive effects of the SCF in reducing the total damage to a structure. As can be seen from the figure, for weak earthquakes with a magnitude of four or five the amount of absorbed energy is nearly equal for both foundation systems. This is so because weak earthquakes do not impose large sliding displacement to the SCF system (i.e. the system has not been fully exploited), and thus the two systems perform nearly the same. But for strong earthquakes (i.e. magnitude > 6), the amount of energy absorbed by the structure on SCF and, consequently, the total damage to the structure d creas dramatically compared with that of the structure on th fixed base foundation.

TEST RESULTS

The general configuration of the test model is shown in Figure 13. The model consists of a single story shear building that rests on a SCF system. The important parameters for the test structure are as follows: plan dimensions of 0.9 m by 0.7 m and height of 1.1.0 m. The story mass is 111.7 kg, the raft mass is 181 kg and the fixed foundation mass is 113.8 kg. The model natural frequency is 6.74 Hz and the estimated damping ratio is 2%. The radius of the concave surface of the foundation is 2.5m, which shifts the fundamental period of the superstructure from 0.148 sec to about 4.0 sec.

In the first stage of the experiment, the model building has been subjected to a harmonic excitation with peak amplitude of 10 m/sec^2 and frequency of 7.6 Hz. Two accelerometers have been used to record the input acceleration to the structure (ground excitation) and the acceleration of the story. The results of the experiment are shown in the figure 14. It can be depicted from the graphs that the SCF system was effective in controlling the response of the structure, even though the frequency of the excitation was very close to the natural frequency of the structure. Also, it is noted that the theoretical model provided an accurate prediction of the building response

As discussed above the Sliding Concave Foundation (SCF) system of the present invention can reduce the lateral seismic forces transmitted to the structure by introducing the flexibility and energy dissipation capability at the foundation level of th structure. Furth rmore, the n w system has a number of advantages. A building support d on the new system behaves like a compound p ndulum during s ismic

excitation. The pendulum behavior accompanied by the large radius of foundation curvature shifts the fundamental period of the system to a high value (e.g. more than 8 sec.), which falls in a frequency range in which none of the previously recorded earthquakes had considerable energy. This results in a large decrease in the structural responses. This represents an important advantage of the SCF system over most of the other systems including the FPS, as it renders the system insensitive to the frequency of the base excitation. Although the pure frictional sliding systems have the same efficiency as the SCF, in reducing the responses of the superstructure, the main advantage of the new system is a significant decrease in sliding displacement. The period of the system increases with the radius of the foundation curvature and the mass moment of inertia of the superstructure. The center of lateral stiffness of the superstructure coincides with the center of gravity of the system, so the effects of torsional vibration are minimized (similar to FPS). Because of friction, SCF system, like other frictional isolation systems, can resist the lateral forces of winds and small earthquakes. This resistant continues until the level of lateral forces exceed the frictional resistant of the sliding surface. However, the SCF system can resist higher level of wind forces than FPS for an equal frictional resistance. This is mainly because, in the SCF the resultant of the wind forces acts at a point that is closer to the center of curvature of the foundation than that of the frictional resistance. The SCF can reduce the base shear and the inelastic absorbed energy of the structure and therefore total damage to the structure. These reductions are completely comparable with those of sliding support system, however the sliding displacement in the case of the new system is significantly less than that of th sliding support system. The structure on a

SCF system is more stable than a structure on most of the other isolating systems, due to the relative locations of the center of gravity of the superstructure and the center of curvature of the foundation.

It will be appreciated by those skilled in the art that a number of the parameters may be varied while staying within the invention described herein. As discussed above, the centre of curvature of the foundation should be above the center of gravity of the building so that the restoring moment can develop. In addition, the radius of the curvature should be at least equal to half of the building height. However, the value of radius of curvature is a matter of design which is based on the level of expected isolation. Further, the restoring moment depends on the radius of curvature and so the value of this moment should be decided in the design process. As well it should be noted that the coefficient of friction is a matter of design and the value of which determines the level of isolation. Similar to any other isolation system that uses friction to dissipate energy, as long as a material can provide the required coefficient of friction and its properties are constant over time, it can be used in SCF.

As used herein, the terms "comprises" and "comprising" are to be construed as being inclusive and opened rather than exclusive. Specifically, when used in this specification including the claims, the terms "comprises" and "comprising" and variations thereof mean that the specified features, steps or components are included. The terms are not to be interpreted to exclude the presence of other features, steps or components.

It will be appreciated that the above description related to the invention by way of exampl only. Many variations on the invention will be obvious to those skilled in the

art and such obvious variations are within the scope of the invention as described herein whether or not expressly described. Further, it will be appreciated that the equations herein are to further describe the invention and they should not be seen to limit or bind the present invention to any particular theory or hypothesis.

REFERENCES

1. Al-Hussaini TM, Zayas VA, Constantinou MC. Seismic isolation of multi-story frame structures using spherical sliding isolation system. Technical report no. NCEER-94-0007, NCEER, State University of New York at Buffalo, 1994.
2. Zayas VA, Low SS, Mahin SA. The FPS earthquake resisting system. Experimental report no. UCB/EERC 87/01, EERC, University of California, Berkely, 1987.
3. Kelly JM. Aseismic base isolation: Review and bibliography. Soil Dynamic and Earthquake Engineering 1986; 5(3): 202-216.
4. Su L, Ahmadi G, Tadjbakhsh IG. A comparative study of performance of various base isolation systems, Part I: shear beam structures. Earthquake Engineering and Structural Dynamics 1989; 18: 11-32.
5. Skinner RI, Robinson WH, Mcverry GH. An introduction to seismic isolation. Wiley; England, 1993.
6. Westermo B, Udwadia F. Periodic response of a sliding oscillator system to harmonic excitation. Earthquake Engineering and Structural Dynamics 1983; 11: 135-146.

7. Mostaghel N, Hejazi M, Tanbakuchi J. R spons of sliding structures to harmonic support motion. Earthquake Engineering and Structural Dynamics 1983; 11: 355-366.

8. Mostaghel N, Tanbakuchi J. Response of sliding structures to earthquake support motion. Earthquake Engineering and Structural Dynamics 1983; 11: 729-748.

9. Yang YB, Lee TY, TSAI IC. Response of multi-degree of freedom structures with sliding supports. Earthquake Engineering and Structural Dynamics 1990; 19: 739-752.

10. Fan FG, Ahmadi G, Tadjbakhsh IG. Multi-story base-isolated buildings under a harmonic ground motion, Part I: A comparison of performances of various systems. Nuclear Engineering and Design 1990; 123: 1-16.

11. Fan FG, Ahmadi G, Mostaghel N, Tadjbakhsh IG. Performance analysis of aseismic base isolation systems for a multi-storey building. Soil Dynamics and Earthquake Engineering 1991; 10: 152-171

12. Vafai A, Hamidi M, Ahmadi G. Numerical modeling of MDOF structures with sliding supports using rigid-plastic link. Earthquake Engineering and Structural Dynamics 2001; 30: 27-42.

13. Zayas VA, Low SS, Mahin SA. Feasibility and performance studies improving the earthquake resistance of new and existing buildings using the friction pendulum system. Report no. UCB/EERC-89/09, EERC, University of California, B-rkely, 1989.

14. Mokha AS, Constantinou MC, Reinhorn AM. Exp rimental study and analytical

prediction of earthquake response of a sliding isolation system with spherical surface. Technical Report no. NCEER-90-0020, NCEER, State University of New York at Buffalo, 1990.

15. Mokha AS, Constantinou MC, Reinhorn AM, Zayas VA. Experimental study of friction pendulum isolation system. Journal of Structural Engineering (ASCE) 1991; 117: 1203-1219.
16. Zayas VA, Low SS. Seismic isolation retrofit of an apartment building. Proceeding of Structures Congress ASCE, Indianapolis, 1991.
17. Zayas VA, Low SS, Mahin SA. Parametric studies on the properties and responses of friction pendulum isolation bearings. Report no. UCB/EERC-93/00, EERC, University of California, Berkely, 1993.
18. Constantinou MC, Kartoum A. Shake table testing of bridge deck on friction pendulum bearings. Report no. UCB/EERC-93/00, EERC, University of California, Berkely, 1993.
19. Peer Ground motions, 2000. A Site of Occurred Strong Earthquakes. www.ames.ucsd.edu/research_units/geotech/PEER motions.
20. Iranian code of practice for seismic resistant design of buildings. BHRC-PNS 253, (2nd ed). Building and Housing Research Center, Tehran, Iran, 1999.
21. Manual of steel construction, allowable stress design (ASD). American Institut of Steel Construction, Chicago, Illinois, 1995.
22. Nurtug A, Suculoglu H. Prediction of seismic energy dissipation in SDOF systems. Earthquake Engineering and Structural Dynamics 1995; 24: 1215-1223.